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A review of islanding detection techniques for renewable distributed generation systems

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ABSTRACT

Islanding detection of distributed generations (DGs) is one of the most important aspects of interconnecting DGs to the distribution system. Islanding detection techniques can generally be classified as remote methods, which are associated with islanding detection on the utility sides, and local methods, which are associated with islanding detection on the DG side. This paper presents a survey of various islanding detection techniques and their advantages and disadvantages. The paper focused on islanding detection using a conventional and intelligent technique. A summary table that compares and contrasts the existing methods is also presented.

Contents

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1. Introduction

Conventional power distribution systems are passive networks, where electrical energy at the distribution level is always supplied to the customer from upstream power resources that are connected to the bulk transmission system. The distributed generation (DG) concept is introduced at the distribution level to exploit the benefits of small local renewable generation. The resources are generally below a couple of MWs and can be wind farms, micro hydro turbines, photovoltaics (PV), and other generators that are supplied with biomass or geothermal energies. The difference between traditional and embedded distribution network systems is illustrated in Fig. 1. In an embedded distribution network system, additional DG resources are supplied near the local load compared with the traditional network system.

The application of multiple DGs in the distribution system is becoming a common practice with the integration of DG resource. This practice is caused by the advantages of DG such as environmental benefits, increased efficiency, avoidance of transmission and distribution (T&D) capacity upgrades, and reduced T&D line losses [1–5]. However, numerous problems should be tackled before the DG units are applied to the networks. These problems include frequency stabilization, voltage stabilization, intermittency of the renewable resources, and power quality issues. The formation of the microgrid (MG), which is cause by the disconnection from the main grid without stopping the energy generation from the DG sources, can also be considered as a drawback of DG [6]. The disconnection of the main source is called islanding, which can be either intentional or unintentional. The purpose of intentional islanding is to construct a power “island” during system disturbances, which are commonly introduced because of the faults. However, the active part of the distribution system should sense the disconnection from the main grid and shut down the distributed generators in countries where island mode operation (MG) is not allowed. Undetected island MG is generally called “unintentional islanding”. Fig. 2 shows the formation of a power island because of an upstream fault in the grid system [7,8].

The unintentional islanding of DGs may lead to several problems in terms of power quality, safety, voltage and frequency stability, and interference [3–5,9–11]. The IEEE 1547–2003 standard specifies a maximum delay of 2 s for the detection of the unintentional islanding condition; the IEEE 929–1988 standard requires the disconnection of the DG if islanded [3,4]. Therefore, uncovering effective solutions to resolve this problem is necessary. Research work on unintentional islanding detection is rapidly growing to ensure that the system is operated under the standard requirements. The literature shows several technical publications related to islanding detection from the past twelve years. Most of the ideas that aimed to resolve the problem were proposed after 2007, which indicates the importance of the research subject.

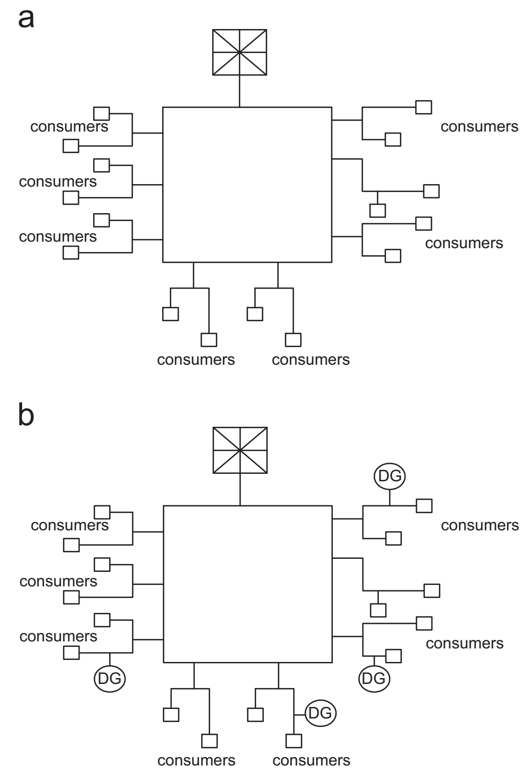


Fig. 1. (a) Traditional distribution system (Traditional Grid System), (b) Generation embedded (Microgrid Networks).

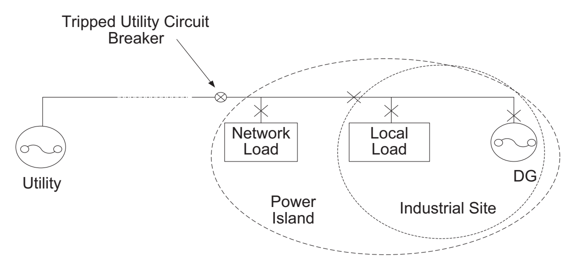


Fig. 2. Illustration of power islanding condition.

2. Islanding detection methods

Various techniques have been developed to detect islanding. These techniques can be broadly classified into central (remote) and local methods as illustrated in Fig. 3. In the following subsections, the details of these methods are explained and evaluated.

2.1. Central (remote) techniques

2.1.1. System state monitoring

System state monitoring is a method for determining system states from a model of the power system network with a reduced number of state measurements. This method is generally regarded as a function of the Distribution Management System (DMS), which is a complementary of supervisory control and data acquisition (SCADA) systems. The method is also used to detect unintentional islanding by monitoring the parameters of the entire distribution system such as voltage and frequency [12]. If the parameter can still be detected from the disconnected area, the occurrence of islanding is detected. This method is highly effective in detecting unintentional islanding if the system is properly instrumented and controlled. However, the cost of implementation is expensive because each inverter requires separate instrumentation and communication equipment. The survey shows that this technique was tested by the PV system. Therefore, other DG types, such as wind turbines and fuel cells, can be explored. The limitation of the high cost of implementation, particularly for small systems, can be addressed using other techniques.

In [6,10], the voltage sensitive devices embedded in the PV-based DG inverter are connected to SCADA system. The loss of mains is detected and notified to the central control system to inform the island mode operation. Real time monitoring of voltage for each generator in the distribution grid can be a cumbersome process with an increased number of DGs connected to the grid. SCADA is also used to monitor auxiliary contact on all circuit breakers between the main source of generation and the DG units [13].

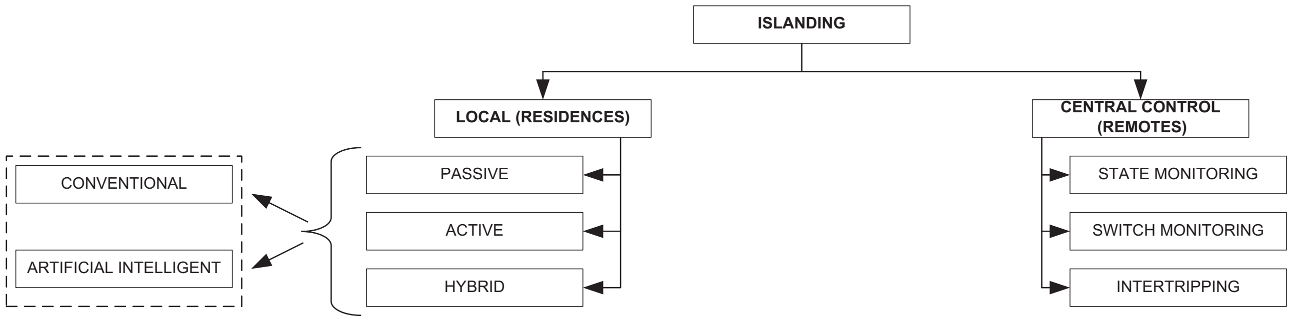


Fig. 3. The classification of islanding detection techniques.

Table 1
Summary of remote islanding detection techniques.

Methods	Advantages	Disadvantages	Improvements
SCADA system	• Communicate with all DG	• Cost implementation high • Difficult to fix	
Transfer trip scheme	• Simple concept • Avoid NDZ	• Expensive • Complicated	• Direct transfer trip can avoid islanding
Wired cable or non-wired	• Easy to be implement	• Cost concern for DG below 2 MW (cost impact can goes up to 50% of total connection cost)	• Needs any possible media to transfer the signals • Concern in remote intertrip signals, where the communication media is outside the control of the user

2.1.2. Switch state monitoring

The SCADA system can be used to monitor the status of the circuit breakers and reclosers that could island a distribution system [3,5]. However, this method requires an improved interaction between the utility and DG units, which leads to extra costs for both utility and DG sides. Transfer trip detection schemes require all the circuit breakers that island the DG to be monitored and linked directly to the DG control, or through a central substation SCADA system. When a disconnection is detected at the substation, the transfer trip system determines which areas are islanded and sends an appropriate signal to the DGs to remain in or discontinue operation.

The transfer trip scheme is incorporated with SCADA to monitor the status of circuit breakers and reclosers [3–13]. The scheme allows for the additional control of DGs through the utility and increases the coordination between the DGs and utility. However, the method has a complexity cost because of the growth of the system complexity, where the transfer trip becomes outdated and requires relocation or updates.

2.1.3. Intertripping

Another method that can be used for islanding detection is intertripping, which is theoretically different from central control techniques. The method detects the opening of a contact at the points of disconnection and transmits the signal to all generation sites that support the respective island zones. Intertripping also generally relies on the communication between the sensors and generating units. These techniques have higher reliability and provide accurate solutions but are uneconomical [14,15].

The above three techniques are used because of their reliability. The review shows that central control techniques are preferable because these techniques can avoid non-detection zones (NDZ), where the power absorbed by the load almost perfectly matches the power generated by the DG [10,16,17].

Central control methods are also not influenced by the number of inverters, size of system, type of generator, and penetration level. However, a tight connection between utility and DG units is needed in applying communication techniques. Table 1 shows a summary of the remote islanding detection techniques.

2.2. Local islanding detection techniques

Local techniques are broadly used to detect islanding based on the measurement of the system parameters at the DG site such as voltage, frequency, current, and harmonic distortion. These techniques can be further divided into passive, active, and hybrid techniques. A literature overview on local islanding techniques was conducted. The statistic notably shows that active and passive techniques have rapidly increase throughout the years.

2.2.1. Passive techniques

Passive techniques monitor the system parameters such as voltage, frequency, harmonic distortion, and current on the DG site at the point of common coupling (PCC) with the utility grid. These parameters vary greatly when the distribution system is islanded. The parameters typically used to detect islanding conditions are frequency and voltage [5,7,18–22]. Various traditional passive islanding detection techniques exist as follows:

2.2.1.1. Under/over voltage and under/over frequency. The under/over voltage (UVP/OVP) and under/over frequency (UFP/OFP) is the oldest technique adapted to protection the distribution system. The protection relays for this technique are placed on a distribution feeder to determine the various types of abnormal conditions. UVP/OVP and UFP/OFP are used to monitor of the grid voltage/frequency exist the limits imposed by the relevant standards [10]. These technique is usually used at all grid connected PV inverters. These protection methods are considered to be based on the power flow at the PCC

Table 2
Comparison of passive islanding techniques.

Method	Implementation speed	Weakness	Improvement
UFP/OFP UVP/OVP	Easy but reaction time unpredictable and variable	Large NDZ	Compared with P-V and P-Q, for constant current controlled inverters
PJD	Difficult in implementation and hard to choose threshold	failed to detect islanding when DG power generation matches the power demand of local load	Controlled by using a PLL
THD	Easy but hard to choose threshold	failed to detect islanded in case of low distortion of voltage and current output of inverter or high quality load	
Voltage unbalance		Not applicable to signal phase system	Combine two or more methods, e.g. Unbalanced voltage and THD of current and voltage magnitude variation

between the utility and PV inverter, which refers to the active power (*P*) and reactive power (*Q*).

However, the primary weakness of the UVP/OVP and UFP/OFP is the large NDZ. Therefore, some improvement was made to overcome the large NDZ components. A method is proposed to reduce the NDZ of UVP/OVP and UFP/OFP by comparing the *P–V* and *P–Q* characteristics of the controlled constant current inverters [23]. The islanding detection based on the performance of the interface control, which is an additional parameter, was implemented in parallel to the UVP/OVP and UFP/OFP to reduce the NDZ.

2.2.1.2. Voltage phase jump detection. Phase jump detection (PJD) requires monitoring the phase difference between the terminal voltage and output current of the inverter for a sudden “jump” [24]. If islanding occurs, the inverter and local load depart from the main system. The PJD technique searches for a rapid change in phase angle to detect islanding. This method has easy implementation because only modifying the phase locked loop (PLL) required by the inverters for utility synchronization is needed. The capability to deactivate the inverter is only required when the phase errors exceed some threshold. The method also does not affect the power quality of the inverter and can be used in multiple inverter systems [12]. However, PJD is unsuitable in detecting islanding for all the operating conditions of the load [1]. The drawback of the PJD leads to a failure in detecting the islanding condition when the DG power generation matches the power demand of the local loads. Nevertheless, the NDZ of the PJD method is smaller than standard over/under protection devices because of the dependence of the PJD method on the only the power factor. This method can be implemented in the inverter using a PLL either in analog or digital forms [25].

2.2.1.3. Harmonics measurement. The measurement of the harmonics (line voltages and currents) is known as the detection of harmonics [26,27]. This method monitors the change of the total harmonic distortion (THD) at the PCC [25]. If the THD exceeds a defined threshold, the inverter should disconnect the DGs. However, selecting a trip threshold, which does not lead to nuisance tripping of the inverter, is easy because the distortion level rapidly changes as the nonlinear load switches on and off [28]. Two monitoring parameters, namely, voltage unbalanced and the THD of current, are also proposed to detect the islanding operation of DG [29]. However, this method is difficult because of the high *Q* factor detection and the threshold selection problem [5].

2.2.1.4. Voltage unbalance. The voltage unbalance (VU) generally varies because of the topology changes of the networks and the load despite the small changes in the DG loading [3,4,29]. Therefore, effectively detecting the islanding operation is possible if the unbalanced of the three-phase output voltage of the DG is continuously monitored.

Special identification was conducted to monitor the VU deviation from the steady state and normal loading conditions. Therefore, each step is compared with the VU identification values and any abrupt VU is identify as islanding.

Jang et al., defined the one-cycle average of the voltage unbalanced and voltage unbalanced variation, which was checked at every 1/4 cycle (4.17 ms) [29].

The survey shows that most of the preferences in choosing passive islanding detection are the cost and simplicity of implementation. Passive techniques are effective for majority of the situation disturbances that occurr in the grid [10].

However, the major drawback of passive techniques is the large NDZ, which fails to detect the islanding condition. The local load affects the determination of the islanding detection. Therefore, those limitations can be answered by active techniques, which are categorized in the next section. Table 2 summarizes the existing major issues of the passive technique method with their advantages and disadvantages.

2.2.2. Active techniques

Active techniques have recently been applied by introducing a small disturbance to grids, which is the response of the intern with the grid and deciding if the grid is in the islanding condition [3,4,10,28,30]. Various active islanding detection with non-artificial intelligent techniques exist, some of which are described and discussed in detail below.

2.2.2.1. Impedance measurement. The impedance measurement method is the same as the passive technique, which measures the system impedance changes caused by islanding. In an active direct method however, a shut inductor is momentarily connected across the supply voltage from time to time, and the short circuit current and supply voltage reduction are used to calculate the power system source impedance [3,4]. A large number of impedance detection methods have recently been proposed because of the belief that this method has no NDZ in the single-inverter case.

Therefore, the experimental study verifies the impedance detection test based on the islanding detection in a single-inverter case [31].

The experiment reveals that the impedance detection method based on islanding detection does have a NDZ in the single-inverter systems. Given the parallel RLC load however, high-*Q* loads cause the most trouble for impedance detection such as with frequency-shifting islanding detection methods. Ensuring that the inverter maximum power point is enabled with impedance detection is important because impedance detection can be a reliable anti-islanding method even for a small duty ratio value. The effectiveness of impedance detection in the single-inverter case is greatly enhanced by the addition of a time-varying phase shift. This improvement comes with an additional cost from the small amounts of sub-harmonics in the PV inverter output. Therefore, other active techniques can be used to surpass the limitation of impedance measurement.

2.2.2.2. Slip-mode frequency shift (SMS). SMS is one of the three methods described in this study that uses positive feedback for islanding detection, namely, amplitude, frequency, and phase.

The method applies positive feedback to the phase of the voltage as a method in shifting the phase and, subsequently, the short-term frequency. The SMS is used to detect the islanding condition because of the easy implementation of the method caused by the involvement of only a slight modification of a required component. SMS is also highly effective in islanding prevention (small NDZ) compared with other active techniques [23].

However, SMS causes system-level power quality and transient response problems at very high penetration levels and feedback loop gains. This problem is common to all three methods that utilize positive feedback.

SMS also introduces a phase shift perturbation, which can lead to noise, measurement inaccuracy, and quantization error in practice. This limitation can be answered by introducing an additional phase shift called the improved-SMS (IM-SMS) [32]. The IM-SMS was verified through digital simulation and experimentation, which result simplicity, easy implementation, and high reliability.

2.2.2.2.1. Active frequency drift (AFD). The principle of the active frequency drift (AFD) or frequency bias method is forcing variations in the inverter output using positive feedback to accelerate the frequency of the inverter current[12,33].

The AFD uses the waveform of the inverter current, which is injected into the PCC. The waveform drifts of the grid is not present as a stabilizing influence [5,12,33,34]. The advantage of AFD is the ease of implementation in microcontroller-based inverters. However, all inverters must have identical AFD or else would fail to detect islanding conditions in the multiple inverter case [5].

AFD is also only effective for purely resistive loads [35]. Therefore, the automatic phase-shift method (APS) is proposed to mitigate the non-detection problem with SMS and AFD. Only the starting angle of the inverter output current is changed using APS based on the frequency of the inverter terminal voltage [36]. However, problems occur in islanding detection such as the assumption of the unity-power factor operation of the PV inverters, which fails in the frequency-shift method or APS, and the unwarranted effectiveness [36].

The rms value and Fourier series coefficients of the current waveform are used to improved the conventional AFD. The operational characteristics of the method are also analyzed, which gave less total harmonic than conventional AFD. This method can reduce about 30% of the THD in the current waveform. Therefore, the method can more rapidly detect the islanding with improved NDZ. However, the method can be further improved using the active frequency drift with positive feedback (AFDPF) [37].

2.2.2.2.2. Sandia frequency shift (SFS). The SFS method, normally known as AFDPF, is an extension of the AFD and is another method that uses positive feedback for islanding detection [25].

SFS is not difficult to implement and has one of the smallest NDZs of all the active islanding detection techniques. SFS has been implemented in combination with Sandia Voltage Shift (SVS)-based islanding detection. This combination is extremely effective [5]. However, SFS has issues in power quality and system stability, which can cause an undesirable behavior in the system response.

The drawback of AFD and AFDPF, which is the degree of power quality caused by the discontinuous waveform, can be overcome using the proposed new phase drift anti-islanding algorithm [19]. In the proposed method, the phase difference of the terminal voltage and current is applied to detect the islanding condition. The method use a current command by increasing the phase difference either k^2 or $-k^2$ when the islanding phenomena occurs. Therefore, this method can reduce the NDZ and minimize the deterioration of power quality.

SFS is also used to detect the deterioration of the islanding condition using multiple PV inverters. The performance of the SFS method is notably dependent on the optimal design of its parameter. Therefore, a mathematical formula is derived to determine the optimal setting of the SFS islanding detection parameters with a multi inverter-based DG, such as PV systems, to eliminate the NDZ condition.

2.2.2.2.3. Sandia voltage shift (SVS). The third positive feedback-based method of islanding detection is the SVS, which applies positive feedback to the amplitude of the voltage. SVS is the most effective in islanding prevention among the three positive feedback-based methods. However, SVS may produce minimal effects on the utility system transient response and power quality.

An active technique was used by adding the disturbance current through the voltage-source control (VSC) to effectively detect the islanding condition. The variation of the time-varying amplitude of the PCC voltage is also determined when the disturbance remains constantly unchanged [20]. This method has a faster detection speed and a smaller NDZ than the normal technique if the suitable accelerating factor is selected.

Karimi et al. suggested a new islanding detection method based on a negative-sequence current injected using VSC [38]. The method detects and measures the negative-sequence voltage at the PCC of the VSC using a unified three-phase signal processor, which is an improved PLL system that gives a high degree of immunity to noise. Therefore, the method allows for islanding detection by injecting a small negative-sequence current (2% to

Table 3
Comparison of active islanding detection technique.

Method	Implementation and speed	Weakness	NDZ
Impedance measurement	Easy and fast		Large for high *Q* load
SMS	Medium and slow	Ineffective under certain load, e.g. RLC resonant load	Large for high *Q* load
AFD	Easy and medium		Large for high *Q* load
SFS	Difficult and relatively fast	Problem in power quality, system stability	Exist for high *Q* load but less compared to others
SVS	Medium and fast	Increased harmonic distortion	Very less

3%). The simulation reveals that the islanding event can be detected within 60 ms under the UL1741 anti-islanding test condition [39].

Bahrani et al. also presented a solution in obviating the NDZ of an existing islanding detection method to prove the method had NDZ in the load parameter space. The method was tested using a multi-DG system and was verified for islanding detection. The experiment revealed that the islanding events can be detected within 120 ms in the worst case scenario because the load parameter is in the NDZ space [39].

The survey shows that an active technique based on islanding detection can defeat the passive technique limitation by giving a small NDZ. However, the active method has better reliability than the passive technique. The main limitation of the active technique is the perturbation in the system. The detection time for the islanding detection is slow because extra time is needed for the system to response to the perturbation. Table 3 summarizes the existing major issues when using the active technique method.

2.2.3. Hybrid technique

The hybrid technique is a combination of the active and passive techniques. The active technique is applied only if islanding is detected based on the passive technique. Some of the hybrid techniques that do not utilize artificial intelligence are briefly discussed.

2.2.3.1. Voltage unbalance and frequency set point. Menon and Nehrir presented a hybrid method based on the positive feedback (PF) and the voltage unbalance and total harmonic distortion (VU/THD) techniques, where in the drawback of both techniques are canceled out when simultaneously applied [40]. The calculation of the VU for each of the DG is used instead of the THD because the VU is more sensitive to disturbance than THD. Therefore, any disturbance applied to DGs could produce a spike in the VU. The technique also efficiently discriminates between the load switching and islanding condition.

2.2.3.2. Technique based on voltage and real power shift. This technique uses an average rate of the voltage change (passive technique) and a real power shift (active technique) to answer the limitations of the active and passive techniques in islanding detection [35]. The technique can detect the islanding condition with multiple DG units operating at a unity power factor.

However, the real power shift (RPS) is applied to the system if the passive technique cannot perfectly detect the islanding condition. RPS can eliminate the injecting disturbance from time to time to detect islanding similar to other active techniques [35]. However, RPS only can change the real power of the DG at the unity power factor. In the proposed method, only one DG changes the real power compared with the positive feedback technique, where all the DGs work together to inject perturbation in the system [35].

2.2.3.3. Voltage fluctuation injection. This technique is based on the voltage fluctuation injection, which can be obtained using a high impedance load [41]. The islanding detection correlation factor (CF) is proposed for small-scale DGs, typically less than 1 kW. The two-stage method, which is the passive technique (rate of change of frequency (ROCOF)/rate of change of voltage (ROCOV)) for the protection scheme, and the active technique (CF) as a backup is applied to attain higher effectiveness. This technique uses digital signal processing to calculate the ROCOF, ROCOV, and CF of the distribution synchronous generator and to accurately decide between islanding and non-islanding disturbances [41].

However, ROCOF is used as a protection scheme, whereas the detection of the output active power variation and reserve VAR detection is used as a backup protection scheme in islanding detection [8]. The NDZ is reduced when the ROCOF is applied with a change in the active technique for islanding detection. The technique can also reduce the insensitivity to the system parameter variation.

2.2.3.4. Hybrid SFS and Q–f islanding technique. The SFS and *Q–f* curve are proposed based on islanding detection to improve the SFS and reduce the NDZ [42]. The optimum SFS is calculated using the analytic formula, where the bacterial foraging algorithm is being used to search the optimal gain of the SFS to eliminate NDZ. The *Q–f* droop curve technique is then added to increase the effectiveness of the SFS-based islanding detection.

2.3. Signal processing methods used for identification of island mode operation

The islanding condition must be detected as quickly and accurately as possible. Therefore, researchers are currently looking into intelligent methods in detecting and classifying the islanding condition. Signal processing techniques have aided researchers in understanding the existence of an island mode operation regardless if the location of control is local or central. The implementation of the signal processing technique allows for the extraction of the hidden features of the measured signals to detect the islanding condition. These extracted features can then serve as inputs to the artificial intelligent (AI) classifier to perform the classification of the islanding and non-islanding detection. Common AI classifiers used in islanding detection include the decision tree (DT), rule-based techniques, artificial neural network (ANN), probabilistic neural network (PNN), fuzzy logic (FL), and support vector machines (SVM).

The signal processing methods present various features, such as time-frequency distribution (TFD) of a time series, which eases the analysis and quantification of the signals regardless of the succeeding classification technique shown in Fig. 4. The linear TFD techniques are popularly implemented in determining the islanding condition because such implementation is faster than those of non-linear methods. Fig. 4 shows the steps involved in performing the islanding condition classification. The following sections describe some of the SP tools used in islanding detection. The islanding detection techniques that use signal processing and the succeeding AI classifiers are discussed further in the following subsections.

2.3.1. Wavelet-transform (WT)

The wavelet theory is the mathematical model for non-stationary signals with a set of components in the form of small waves called wavelets [43]. The original wavelet is generated from one original wavelet called the mother wavelet, which is then further extended to allow the wavelet to analyze the non-stationary signals in the frequency band. WT can be either continuous (CWT) or discrete (DWT). Using a wavelet is advantageous because the wavelet does not need to assume the stationary or periodicity of signal. The WT is capable simultaneously comprehending time and frequency information because wavelet has long windows at low frequencies and short windows in high frequencies. Therefore, WT can supervise the discontinuities and transients in time-varying signals to enhance islanding detection studies.

CWT is applied using an online measuring technique for the voltage in DG units [44]. The Mallat decomposition algorithm was used in extracting the noise in the signals to eliminate the noise.

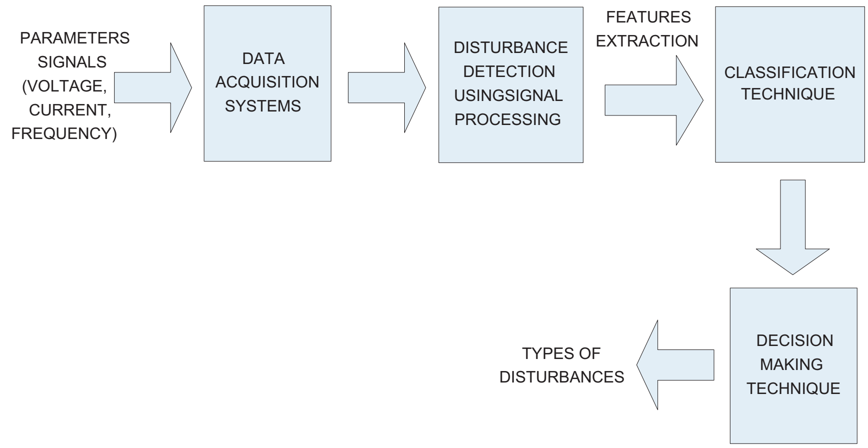


Fig. 4. Basic blocks of intelligent islanding detection technique and classification.

The technique creates numerous coefficients to reduce the computational efficiency of the algorithms, which allows researchers to focus more on using the DWT technique instead of the CWT technique.

Pigazo et al. proposed a WT method to obtain the time localization of signals from a single-phase PV system [45,46]. The method used five decomposition levels for the islanding operation mode, and Biorthogonal 1.5 was implemented for the anti-islanding detection algorithm. The advantage of the technique is the reduction of the number of sensors needed and the minimized computational burden of the anti-islanding algorithm.

Hsieh et al. proposed a WT-based approach to monitor voltage and frequency variations, where the Daubechies wavelet served as the basis [47]. Some of the useful features in this method are the improvement in the islanding detection capability of protection relay, the simultaneous observation of information, and the simplicity to programming. The technique can give feasibility, flexibility, and robustness to the proposed method as tested in several scenarios.

In [48], WT was applied to a negative sequence voltage and current signals. The change in energy and standard deviations coefficients were then used to distinguish between islanding and non-islanding events. Daubechies db4 was used for islanding detection in this technique. The islanding can clearly be detected for one cycle signal data using first level wavelet coefficients (d1) of the energy and standard deviations. DWT with Daubechies db4 was similarly used to reduce the NDZ to zero. Db4 is used because of its compacted and localization properties [49]. Db4 also utilizes the spectral changes in higher frequency components by applying second level wavelet coefficients (d2), which are more robust and less affected by noise.

One of the limitations of using DWT is the merging of the frequencies, especially at high frequencies. Therefore, the wavelet packet transform (WPT) based on voltage and current signal at PCC is introduced in [50]. The method is based on the rate of change of power (ROCOP) from the DG power output. The method introduced a new index called the node rate of change of the power (NROCOPI), which is used to quantify the change of the power at each WPT sub-band. Daubechies of order 10 served as a basis of WPT, which had a smaller number of wavelet coefficienta compared with others without affecting the accuracy of the results.

In [51], the wavelet was applied to detect the islanding condition of wind turbines. The method used DWT with Daubechies db5 to determine the best wavelet basis function with accurate results. However, all these methods necessitated the measurement of several electrical quantities, which requires much time in detecting islanding. Therefore, the wavelet was used to detect islanding using only the terminal current of DG as a parameter in [52]. The "Haar" mother wavelet was used to detect the islanding event because this wavelet requires the least decomposition levels and, therefore, the least detection time for islanding detection. In [53], WT based on detecting the stand-alone operation of DG systems was introduced.

2.3.2. S-transform

The major drawback of WT is the inability to detect islanding conditions under a noisy condition. Therefore, a modification of WT called S-Transform was introduced [54–56]. S-transform produces a time-frequency representation of a time series and has a frequency dependent resolution that simultaneously localizes the real and imaginary spectra. S-transform also provides multi-resolution while retaining the absolute phase of each frequency component, which is useful in detecting disturbances in the presence of noise.

In [55,56], the S-transform was used to extract the negative sequence voltage during an islanding event. The energy content and standard deviation of the S-transform contour was clearly shown in detecting islanding events and disturbance because of load rejection. In [57], the negative sequence voltage and current processed through the S-transform and spectral energy content was calculated. Therefore, the previous techniques of the S-transform clearly required the energy content to detect the islanding condition. The drawback of S-transform is the need for more computation time and memory to process the signal than other techniques. Table 4 summarizes the signal processing techniques in islanding detection.

2.4. Intelligent classifiers

The information generated by any type of signal processing method can be used to identify the existence and characteristics of the island mode operation. In this section, the use of intelligent classifiers are investigated.

2.4.1. Artificial neural network (ANN)

The artificial neural network (ANN) is a computational structure model of a biological process that attempts to implement the mathematical model instead of using a biological brain neural network in which the brain contains all the useful information and the data memory [58]. This model has numerous interesting and attractive features that can be used to identify any changes in the data. Therefore, the model is widely used in numerous areas,

Table 4
Comparison of SP in islanding detection at distributed generation.

References	SP method	Parameter	Key indicator	Islanding detection (time detection)
Zhu[44]	CWT (Wavelet)	Voltage, Current, Power	Modulus local maxima	0.6 s (rate of change of frequency)
Pigazo [45,46]	DWT (Wavelet)	Voltage, Current, Power		Less than 2 s (45 ms)
Samantaray [48]	DWT (Wavelet)	Voltage and current signals. Change in energy and standard deviation	d1 Coefficients	
Hanif [49]	DWT (Wavelet)	Spectral change of PCC voltage	Energy value of second level wavelet coefficient	2.5 power frequency cycles
Morsi [50]	Wavelet Packet Transform (WPT)	Voltage and current at PCC	NROCOPI	
Karegar [51]	DWT (Wavelet)	Voltage	Fifth decomposition level.	Less than 0.2 s
Shariatinasab [52]	DWT (Wavelet)	Terminal current of DGs	third decomposition level	One third of cycles (less than 5.5 ms for 60 Hz)
Ray [54]	S-transform	Voltage	Coherency	
Ray [55], [56]	S-transform	Voltage	Energy and standard deviation indices	

including in islanding detection [59–66]. The ANN is usually used with a signal processing technique such as WT.

Yin presented the combination of the signal processing and the ANN classifier for islanding detection [28]. The output voltages of the inverter were sampled, and the signal frequency domain was obtained using FFT. Immunological principles were then used, where two modules (T-module and B-module) were developed to respond to inverter islanding. The T-module was used to detect the islanding conditions, and the B-module played role in improving the detection coverage space. The experiment and data analysis revealed that the algorithm can effectively detect the islanding condition of the inverter.

In a related work, a hybrid technique was approached using ANNs in detecting the islanding condition [67]. This ANN acted like machine learning technology in processing and analyzing the large set of data from the simulation. This AI compensator was embedded in an automatic voltage regulator (AVR) control loop.

In [8], the ANNs were combined with WT, which is capable of decomposing the signals into different frequency bands. The features are then trained using the ANN model to identify the islanding condition. The approach can detect islanding conditions with a high degree of accuracy and high-quality factor of load performance. This technique is also suitable for multiple DG applications.

ANNs were also combined with the wavelet to detect islanding [68]. The DWT was used to extract the feature from current signals. The signal was then extracted using a correlation coefficient and was validated using ANN. Only one signal was analyzed, and only one of the ANN input is used to detect the islanding condition. This algorithm showed high classification efficiency, which makes the algorithm suitable for a practical system.

2.4.2. *Probabilistic neural network (PNN)*

Another classification technique that can be used is the probabilistic neural network (PNN), which is based on a Bayesian classifier technique commonly used in classical pattern-recognition applications [69]. PNNs contain four layers, which are the input layer, pattern layer, summation layer and output layer, where each layer has its own function in classifying the features [70]. A PNN does not require a learning process.

The DWT integrated with PNN was proposed for the classification technique in [71]. The combination used the multi-resolution analysis (MRA) of the DWT and the Parseval′s theorem to extract energy distribution features at different resolution levels. The features were then classified using the PNN. In [72], PNN were also combined with WT to detect islanding. The features from the wavelet analysis were used as an input of the PNN, and the output was the class of the fault location. The analysis found that PNN is a very precise way of classifying the location of the fault.

PNN with various parameters were derived at a target DG location to detect the islanding condition [73]. The author also compared other classification techniques such as the DT and radial basis function techniques.

However, PNN is proven to be more effective in islanding detection than other techniques. PNN is also proven to reliable in detecting islanding condition because of the simulation model and real-time digital simulator test.

In [74], a Bayesian passive technique using ESPRIT was proposed, which is a parametric estimation technique that utilizes special quantities to estimate a certain parameter of a signal. A statistical signal-processing algorithm was used to extract the features from the voltage and frequency at the PCC. A cross-validation and a test of accuracy of the method was conducted in several cases to estimate the performance of the proposed technique in islanding detection.

2.4.3. *Decision trees (DT)*

Another classification technique is the decision tree (DT). In [75,76], DT was trained, and the online performance of DT was evaluated in a controlled islanding strategy. DT was trained in simulation on a particular pre-fault operating point. The analysis revealed that the proposed method achieved three main objectives that can be correctly classified for all training cases. However, limitations, such as the dependence of the threshold on the splitting criteria for the corresponding DT, were found. This splitting criterion is also a complex task and can affect the DT technique for classification problems. The criterion has a misclassification rate of 16.6% for islanding detection, which leads to an 83.3% islanding detection accuracy. In [77], DT was used with a combination of DWT. The classifications extracted the features from the transient voltage and current signals using the DWT, where the DT classifier was used to identify the islanding condition. The authentication test performed had more than 98% classification accuracy with a 95% confidence level and a response time of less than two cycles. However, this technique was modified and applied in hardware as presented in [78]. The band pass filter was used to replace the function of DWT. The experiment had 94% accuracy in classifying the islanding and non-islanding and took 14 ms to detect the power island.

Table 5
Comprehensive analysis.

References	SP method	Classification	Recognition rate (RR)
Yin [28]	FFT	ANN	
Ghazi [59]		ANN	88.9
Fayyad [9]	WT	ANN	95.0
Nozahy [60]	DWT	ANN	99.0
Lee [63]	DWT	ANN	90.0
Najy [66]	ESPIRIT	Naïve-bayers	100.0
Arroudi [68]		DT	83.33
Lidula [69]	DWT	DT, CART	98.00
Paul Pham [70]	DWT	DT	94.0
Lin [71]		DT	100
Sun [73]		DT	98
Samantaray [77]		DT, MFs	100

The C4.5 DT was introduced for islanding detection in a DG system by Lin and Dong [79]. The main advantage of C4.5 DT is the minimization of the NDZ, the ability to operate under various operations, and the different network topology. However, the result from the C4.5 DT was not always the best result because the technique can be improved with other optimization methods such as the pruning method of DT. Thomas and Terang similarly proposed an islanding condition using the DT approach [80]. The technique obtained the threshold setting by selecting a new set of parameters, such as current, voltage, active and reactive power, power factor, and frequency. The parameters were easily measured, and the pattern classification was obtained using DT from MATLAB®. However, the system information of PMU measurements was used with DT classifier in [81]. DT was used to detect abnormal system operation behaviors related to islanding possibility.

Lidula et al. compared several classification techniques such as DT, neural network and SVM [82,83] to identify the best classification accuracy in detecting the islanding condition, where the DT is said to be the best classification technique, followed by the neural network and SVM.

2.4.4. Fuzzy logic (FL)

The fuzzy logic (FL) technique can also be applied as a classification technique in islanding detection.

In [84], FL based on three measurement parameters, which are voltage, ROCOF, and active power derivative (ROCOP), was proposed. The FL was applied only when the situation was uncertain or unclear in detecting the islanding.

In [85], FL was introduced from the transformation of DT, where the combination of fuzzy membership functions (MFs) and the rule base were used to develop the fuzzy rule based. This proposed technique was easy to implement for online islanding detection and can handle uncertainties such as noise. The technique proposed was tested with and without the noise and performed perfectly with 100% detection rate cases in islanding.

However, fuzzy classifiers have limitations such as being highly abstract, the heuristic need for experts for rule discovery, and a lack of self-organizing and self-tuning mechanisms of NN, which necessitates exploration of other intelligent techniques. Table 5 summarizes some of the benchmark works in islanding detection.

3. Conclusion

In this paper, an extensive analysis of the various systems of islanding detection techniques in a power distribution system has been presented. The necessary features of islanding detection techniques and the potential of local and remote techniques used in the system have been investigated. Some of the utilities and customer experiences have been outlined. Various intelligent system applications in islanding detection have also been discussed.

About 85 research publications were classified, discussed, and appended for quick reference. An overview of the possible techniques used to determine the islanding condition is given and the improvement made on these techniques are highlighted for the convenience of readers and to create a broad spectrum. The overview can be reviewed through annotated bibliographies.

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